Modern Physics Letters B, Vol. 22, No. 11 (2008) 869–874
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DELAMINATION MONITORING OF QUASI-ISOTROPIC CFRP LAMINATE USING ELECTRIC POTENTIAL CHANGE METHOD

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Real-time detection of delamination in carbon fiber reinforce plastic (CFRP) laminates has been requiring to maintain the structural reliability of aircraft. In this paper, electric potential change method (EPCM) was applied to monitor delaminations in quasi-isotropic CFRP laminate. As the coefficient of thermal expansion and mold shrinkage factor of carbon fiber and epoxy matrix is different, residual stress is developed in the laminate during the fabrication process of curing. The local strain variation due to delaminations was measured by EPCM utilizing the piezoresistivity of the laminate itself. Finite element simulation was performed to investigate the applicability of the method.

1. Introduction

Carbon fiber reinforced plastic (CFRP) laminate is very sensitive to an impact. Even a low impact creates a delamination and deteriorates the mechanical property of the laminate. Monitoring for delamination is indispensable to maintain the reliability of CFRP structure.

The authors introduced electric potential change method for delamination identification of CFRP laminate [1, 2]. Electric current was applied to a laminate from the electrodes which were mounted on the laminate surface. Delaminations were estimated by electric potential changes between electrodes due to a delamination. Delaminations in cross-ply laminated beams were successfully identified. As quasi-isotropic laminates are often used for actual structures of aircraft, the applicability of the method for the laminate was investigated analytically. Strong electric anisotropy of the quasi-isotropic laminate, however, made simple application of the method difficult [3].

In this paper, a new concept for delamination identification using electric potential change method was proposed to resolve the problem. Strain variation on a laminate surface due to delaminations was detected as electric potential changes utilizing its piezoresistivity. The applicability of the method for delamination identification in quasi-isotropic CFRP laminate was investigated by means of finite element analyses.

†Work partially supported by Grant Young Scientists 2006 18860071 of JSPS.

2. Analytical Method

2.1. *Finite element model*

Numerical analyses were performed with commercially available finite element code ANSYS. Specimen configuration was 100 mm long, 50 mm wide and 4 mm thick as shown in Figure 1, which was supposed as a coupon specimen cut from the component. Stacking sequence was quasi-isotropy of $[0_2/90_2/\pm45_2]_s$. Carbon fiber woven fabric (CF fabric) was stacked on both surfaces of the laminate. Glass fiber woven fabric (GF fabric) was inserted between the CF fabric and the quasi-isotropic laminates (see Figure 2). GF fabric was an insulative layer by which electric current flows only in the CF fabric layer.

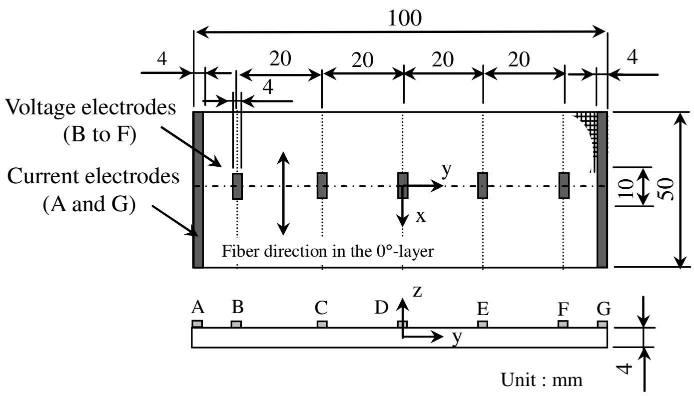

Fig. 1. Configuration of laminate.

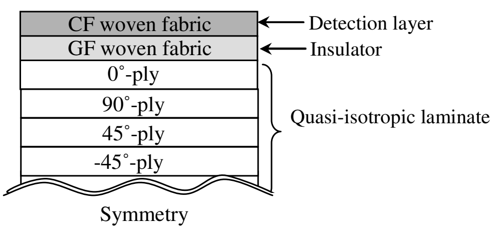

Fig. 2. Stacking sequence of laminate.

CFRP laminate has residual stress, which is developed in the fabrication process of curing [4, 5]. Discrepancies of coefficient of thermal expansion (CTE) and mold shrinkage factor (MSF) between the fiber and the matrix develop residual stress in the laminate. Strain variation due to the release of residual stress by delaminations, therefore, may be observed on the laminate. A local variation of surface strain due to a creation of delaminations is detected as electric potential changes utilizing the piezoresistivity of the CF fabric [6–8]. CF fabric is often used in actual structures on purpose to protect laminate surfaces. Insertion of GF fabric as insulative layer is easy to fabricate.

Two current electrodes (electrode A, and G) were mounted on a laminate surface. Five voltage electrodes (electrode B, C, D, E, and F) were also mounted on the same surface with spacing of 20 mm. All the electrodes were, therefore, mounted on only one side of the laminate. The electrodes were placed parallel to the fiber direction in the 0°-ply. In the finite element analyses, electric potentials of the nodes at each electrode were coupled to have same electric potentials.

Material property of unidirectional carbon fiber lamina was E_L = 160 GPa, E_T = 8 GPa, G_{LT} = 3 GPa, ν_{LT} = 0.34, ν_{TZ} = 0.4. CTE of the fiber and the matrix was $\alpha_f = -0.1 \times 10^{-6}$, $\alpha_m = 141 \times 10^{-6}$ from which CTE of the lamina was calculated using the rule of mixture. Fiber volume fraction was supposed as $V_f = 0.6$. MSF of the matrix α_{cure} (= 0.01) was included with the CTE of the matrix α_m.

$$\alpha_m = \alpha'_m + \frac{\alpha_{cure}}{\Delta T} = 141 \times 10^{-6}, \tag{1}$$

where $\alpha'_m = 50 \times 10^{-6}$ is CTE of the matrix in which MSF was not included. It was supposed that the laminate was cooled ΔT = 110°C from cure temperature of 130°C to room temperature of 20°C in the fabrication process.

Material property of CF fabric was E_L = 80 GPa, E_T = 10 GPa, G_{LT} = 5 GPa, ν_{LT} = 0.03, ν_{TZ} = 0.05, $\alpha_L = 2 \times 10^{-6}$, $\alpha_T = 10 \times 10^{-6}$ and GF fabric was E_L = 40 GPa, E_T = 10 GPa, G_{LT} = 2 GPa, ν_{LT} = 0.03, ν_{TZ} = 0.05, $\alpha_L = 6 \times 10^{-6}$, $\alpha_T = 10 \times 10^{-6}$.

Ply thickness of a unidirectional lamina and woven fabric lamina was supposed as 0.22 mm and 0.12 mm respectively, from which a total thickness of the laminate was 4 mm.

2.2. *Delamination*

In-plane square-shaped delamination was supposed in the analyses. The delamination was made between all the interlaminars. The size of the delamination was 8 mm. Matrix cracks were made at the center of the delamination along the fibers in each lamina. The matrix cracks had same length with the delamination.

2.3. *Piezoresistivity of carbon fiber woven fabric*

Initial electric conductivity and gage factor of the CF fabric was σ_L = 10000 S/m, σ_T = 20 S/m, and $K_L = 3$, $K_T = 4$ respectively. Strain variation due to a creation of delaminations was calculated at all the finite elements. As electric conductivity may change with proportional to the strain, it was modified at every finite element [6–8].

$$\sigma = \frac{\sigma_{int}}{(1 + K\varepsilon)}, \tag{2}$$

where σ_{int} is an initial electric conductivity and ε is a strain. Electric conductivity of every finite element was replaced by the corresponding electric conductivity which was proportional to the strain at the element in the CF fabric layer. As GF fabric layer was an insulative layer, small value of electric conductivity was assigned in the calculation. Electric potential change was, then, recognized in the CF fabric layer after a creation of delaminations due to the variation of surface strain.

2.4. *Electric potential change method*

Electric current of 100 mA was applied at a current electrode A and another current electrode G was set to be 0 V. Electric potential of the laminate were calculated with and without delaminations. Electric potential changes between electrodes due to delaminations were obtained by subtracting the results. The electric potential changes between electrodes were normalized.

$$\Delta p_i = \frac{P_i - P_{i0}}{L}, \; L = \sqrt{\sum_{i=1} \left(P_i - P_{i0}\right)^2} \; , \tag{3}$$

where P_i and P_{i0} (i = BC, CD, DE, EF) are electric potentials between electrodes with and without delaminations. Response surface was obtained using the normalized electric potential changes as predictor variable, and delamination location as response variable. Quadratic equation was used as response surface.

3. Results and Discussion

3.1. *Strain variation on laminate surface due to delaminations*

Figure 3 shows calculation result of y-directional strain variation on laminate surface due to delaminations when it located at x = y = 0 mm. Calculation result showed large strain variation around the delamination due to the release of residual stress in the laminate.

3.2. *Electric potential change due to surface strain variation*

Figure 4 shows calculation result of electric potential change on the laminate surface due to surface strain variation by delaminations at x = y = 0 mm. Electric current was applied from electrodes A to G. The local strain variation due to the delaminations made local variation of electric conductivity of CF fabric, which resulted in the electric potential change on the laminate surface.

3.3. *Delaminations identification*

Response surface was obtained using the calculation results by finite element method (FEM). FEM analyses were performed for multiple cases: delaminations locations of x = –10, 0, 10 mm and $-40 \le y \le 40$ mm with spacing of 5 mm. A total of 51 runs of FEM analyses were performed to obtain training data of response surface. FEM analyses were also performed with delaminations locations of x = –5, 5 mm and $-40 \le y \le 40$ mm with spacing of 5 mm. These 33 delaminations were also estimated using the response surface.

Figure 5 shows estimation results of delaminations locations. A diagonal line shows exact estimation. The adjusted coefficients of multiple determination of the response

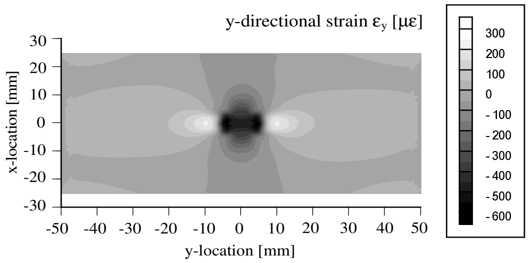

Fig. 3. Contour plot of y-directional strain variation on laminate surface.

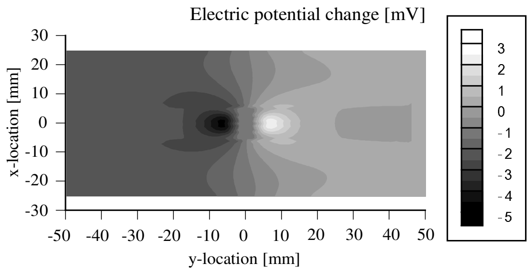

Fig. 4. Contour plot of electric potential change on laminate surface.

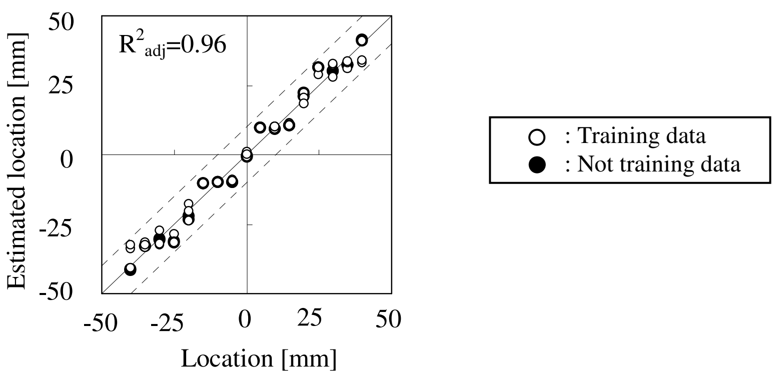

Fig. 5. Estimation results of delaminations locations.

surface was $R^2_{adj} = 0.96$, which indicates regression accuracy of response surface [9]. The response surface, therefore, showed good accuracy of regression. The 33 delaminations which were not used as training data could also be estimated accurately. The applicability of the method for delamination identification was shown by finite element simulation.

4. Conclusions

New concept for delamination identification in quasi-isotropic CFRP laminate was proposed to resolve the problem of previous electric potential change method. Delaminations with matrix cracks developed local strain variation on laminate surface due to the release of residual stress. Electric potential change due to the strain variation was developed by the piezoresistivity of the CF fabric. Delaminations locations were estimated from the electric potential changes. Numerical simulation indicated the applicability of the method for delamination identification.

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